

# Design and Fabrication of Thin-Film Multijunction Thermal Converters at NIST and Sandia National Laboratories

Thomas E. Lipe, Joseph R. Kinard  
Electricity Division  
National Institute of Standards and Technology\*  
Gaithersburg, MD 20899-8111 USA

Thomas F. Wunsch, Ronald P. Manginell  
Sandia National Laboratories†  
Albuquerque, NM 87185-0665 USA

**Abstract** - We report on the results of a collaborative effort between the National Institute of Standards and Technology and Sandia National Laboratories to design, fabricate, and test multijunction thermal converters (MJTCs) based on thin-film technology. These devices are specifically intended for the measurement of ac current and voltage using ac-dc transfer techniques, but have many other possible applications, including the direct measurement of electrical quantities, the measurement of gas flow, and the measurement of vacuum and leak rates. The paper will provide descriptions of the motivation for the project, the design and fabrications of the MJTCs, the electrical and physical properties of the MJTCs and results on the devices produced by the collaboration.

Keywords: Ac-dc difference, Reactive ion etching, Multijunction thermal converter, Thermal converter

## I. INTRODUCTION

Thermal transfer standards form the basis for the measurement and calibration of ac voltage and current in terms of fundamental dc standards at national metrology institutes, high-level calibration laboratories and for manufacturers of electronic and test equipment. Although thermal transfer standards may contain multiplying resistors or current shunts to provide different voltage and current ranges, the primary element is the thermoelement or thermal converter. A thermoelement consists of a heater structure with one or more thermocouples attached to it by an insulating bead. In practice the thermoelement is used to compare the heating effect of an unknown ac signal to that of a known dc signal. The difference between the ac signal and the average of both polarities of the dc signal required to match the ac signal is known as the ac-dc difference of the thermal converter.

Traditional converters are fabricated with heaters made of a resistive wire and thermocouples composed of two dissimilar metallic wires joined at a glass or ceramic bead. The number of thermocouples varies from one for single-junction thermal converters (SJTCs) up to 100 or more for multijunction thermal converters (MJTCs). MJTCs have significant advantages over SJTCs, and, if carefully designed and fabricated, can be made to have ac-dc differences below 1  $\mu\text{V/V}$  at a few volts and at

---

\* NIST is part of the Technology Administration, U.S. Department of Commerce.

† Sandia is a multi-program laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy under contract DE-AC04-94AL85000.

audio frequencies. For the smallest uncertainties at audio frequencies, MJTCs are generally used, and a group of MJTCs forms the primary standards at NIST.

## II. DESIGN AND FABRICATION

We describe thin-film MJTCs that have heaters and thermocouples fabricated on a silicon substrate that has an area etched away to form a thin membrane that provides thermal isolation from the Si substrate[1,2]. The characteristics of the heater structure are optimized through numerical thermal simulation and designed to provide a uniform temperature distribution across the central region where 100 thermocouple pairs are connected in series. Contributions to ac-dc difference from thermoelectric effects such as first-and second-order Thomson and Peltier effects are further reduced by the appropriate choice of heater alloy. The silicon frame provides a good heat sink for the thermocouple cold junctions and reduces the Peltier effect at the contact pads. These thermal and physical design characteristics also contribute to very small dc-reversal errors. Drawings of the converters are shown in Figure 1, and the layout and cross-section of a film MJTC is shown in Figure 2.

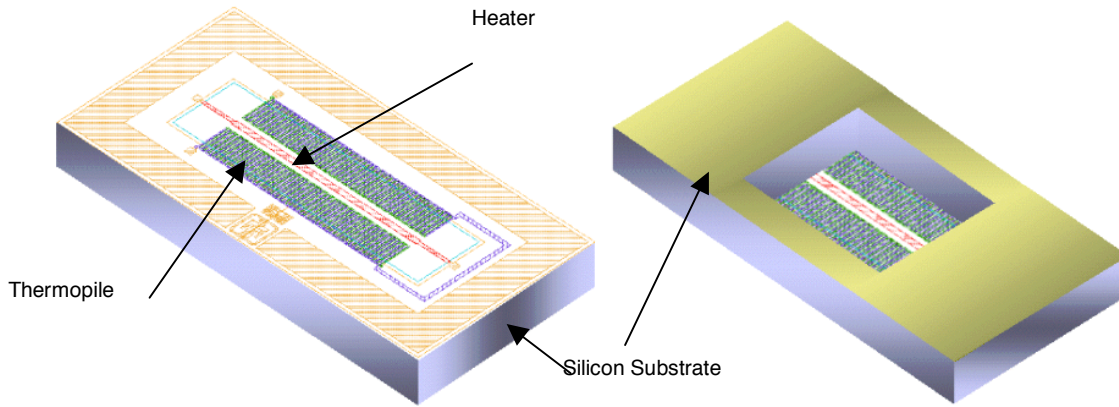


Figure 1. A conceptual drawing of a thin-film MJTC (6 mm x 3 mm x 0.4 mm) with 100 thermocouples connected in series and a 400 ohm heater. On the left is a top perspective view. On the right, is a perspective view of the backside of the die. The thermopile and heater are visible through the transparent dielectric membrane in the backside view. The obelisk, which is located under the heater, has been omitted in this drawing for clarity.

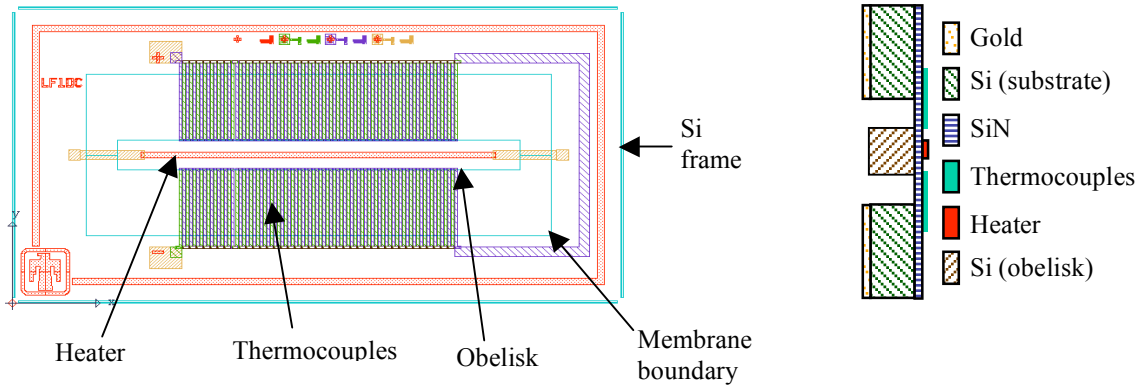


Figure 2. Layout (left) of a coaxial thin-film MJTC showing the various features of the design, and a cross-sectional view (right), showing the various layers comprising the MJTC.

The converters are fabricated on commercially available silicon substrates coated with low-stress nitride 1  $\mu\text{m}$  thick on top of an  $\text{SiO}_2$  etch stop layer 0.5  $\mu\text{m}$  thick. Deep reactive ion etching is used to remove the silicon beneath the heater and the hot junctions of the thermocouples, forming an isothermal membrane. We remove any remaining  $\text{SiO}_2$  under the membrane by a dip in buffered HF.

Thermal integration of the signal is required to achieve time constants sufficiently long for these devices to have small low-frequency errors. To provide time constants long enough for measurement of frequencies as low as 10 Hz, a silicon obelisk is left unetched directly beneath the heater to increase the thermal mass. Unfortunately, with ac signals applied, the addition of this obelisk introduces a negative, frequency-dependent ac-dc difference due to the signal coupling through the dielectric membrane and into the obelisk and increasing the heating effect of the ac signal. Work is underway to reduce this error by using high-purity silicon wafers and by compensation techniques.

The chips are mounted and bonded in 40 pin, ceramic, leadless chip carrier packages that are suitable for either nitrogen fill or vacuum sealing. Because none of the heat is convected away from the heater, vacuum mounted chips have higher sensitivities and longer time constants, qualities that are desirable for applications requiring the highest possible performance. The packages have nonmagnetic feedthroughs to reduce skin effect at higher frequencies.

Thermal converters may be used to measure either voltage or current. The present NIST working standards for voltage measurements are SJTCs composed of 1 V and 2 V thermoelements (in series with multiplying resistors for higher voltages) with outputs of about 10 mV at full-scale input. Since thermal converters are roughly square-law devices, these SJTCs are useful only down to about 50 % of their rated input voltages. With up to 100 thermocouples on a chip, MJTCs provide a much larger output emf, and so are useful at inputs of 25 % or less of full scale. This property of MJTCs is important for voltage scaling applications. Measurements of film MJTCs suitable for use as working standards, an example of which is shown in Figure 3, indicate that the ac-dc differences of these devices are consistent with the ac-dc differences expected from an SJTC at the same input level.

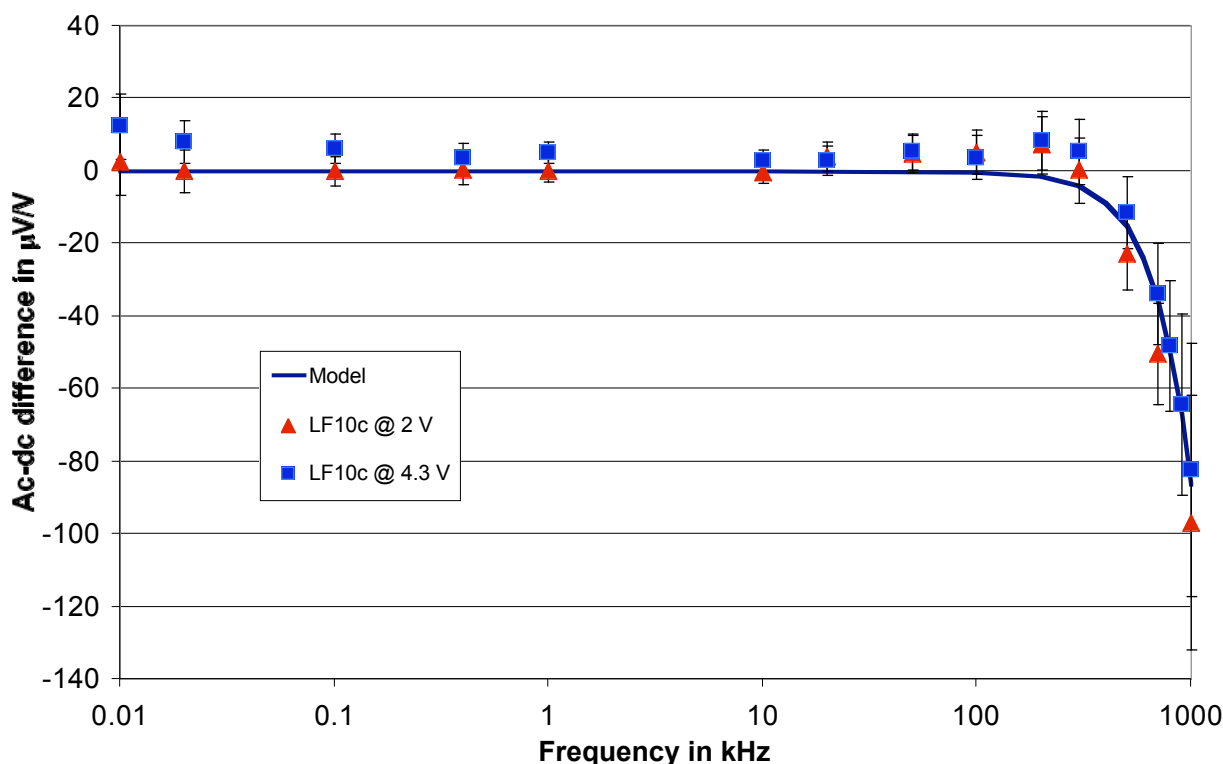


Figure 3. Measured ac-dc differences of a 400  $\Omega$  heater, thin-film MJTC at two different voltage levels. Bars represent the NIST calibration uncertainty ( $k = 1$ ). The predicted frequency response modeled for the presence of the obelisk is also shown

For the calibration of current, the NIST reference standards for ac-dc difference are thermoelements rated from 2.5 mA to 20 A. As replacements for existing standards, new thin-film MJTCs are being fabricated with heaters suitable for currents of 1 A or more, and to accommodate even higher currents, film MJTCs are mounted in multiconverter modules. These modules have several converters with heaters connected in parallel and mounted on a double-sided printed circuit board, shown in

Figure 4, with the chips symmetrically spaced around a circle. The thermocouple outputs of each MJTC are connected in series to achieve a very high output from the module. The ac-dc differences measured for four film MJTCs individually as an ensemble in the multiconverter module are presented in Table 1. The data indicate that the module agrees well with the individual chips at audio frequencies. The divergence at high frequencies is due to transmission line effects in the multimodule. Work continues to design MJTCs useful at higher currents, and multiconverter modules for currents up to 20 A

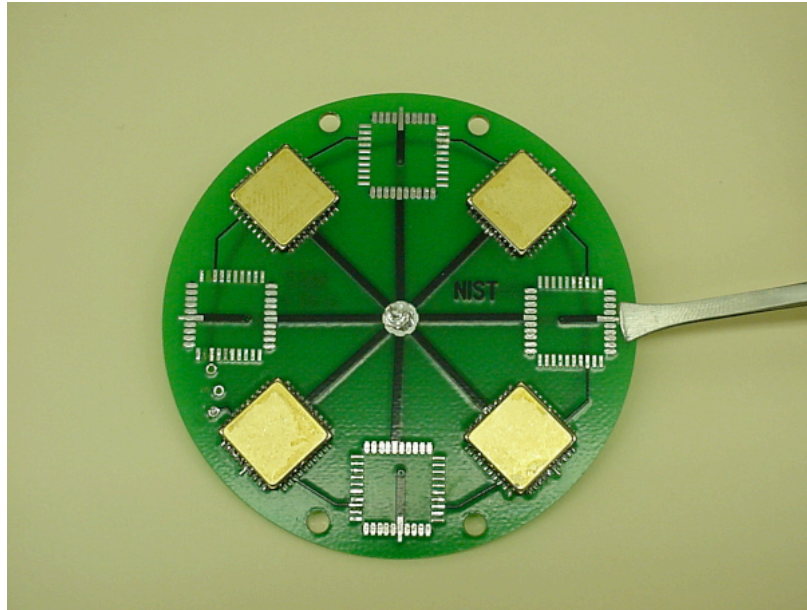


Figure 4. Photograph of a multi-module circuit board populated with four converters. The packages are 12 mm on a side.

Table 1. Measured ac-dc differences for four thin-film MJTCs with nominally rated 50 mA heaters and a multiconverter module populated with the same four chips. The uncertainties are the  $k = 1$  combined uncertainties for the measurements.

FMJTC Serial Number	Applied Current mA	Output Emf mV	Ac-dc Difference ( $\mu\text{A/A}$ )				
			20 Hz	1 kHz	20 kHz	50 kHz	100 kHz
56B4	40	23		$-8 \pm 7$			$-13 \pm 10$
56B6	40	24	$-20 \pm 8$	$-8 \pm 7$	$-6 \pm 7$	$-5 \pm 7$	$-16 \pm 10$
56D2	40	21		$-8 \pm 7$			$-14 \pm 10$
56E6	40	26	$-19 \pm 8$	$-8 \pm 7$		$-5 \pm 7$	$-15 \pm 10$
Module	200	104	$-12 \pm 8$	$-10 \pm 7$	$-8 \pm 7$	$-14 \pm 7$	$-35 \pm 10$

### III. OTHER APPLICATIONS

Although the collaboration between NIST and Sandia National Laboratories is specifically targeted to the design and fabrication of thin-film MJTCs for ac-dc difference metrology, these devices have the potential to be used in other applications. Among the applications appropriate for film MJTCs are:

- Sensors in electronic measurement and test equipment
- Vacuum sensors more sensitive than traditional wire sensors
- Infrared detectors with the addition of an absorbing material to the heater
- Gas-flow sensors for low flow applications

### III. CONCLUSION

We are making multijunction thermal converters using Deep Reactive Ion Etching and other techniques associated with microelectronics fabrication. The devices being fabricated now have small ac-dc differences and are suitable for use as working standards. New converters and multiconverter modules are being designed for use at currents up to 20 A. Vacuum packaging is being used to improve efficiency and performance of these film MJTCs. Work continues to improve the performance of these devices in anticipation of their use as primary standards of ac-dc difference.

### REFERENCES

- [1] T. F. Wunsch, J. R. Kinard, R. P. Manginell, T. E. Lipe, O. P. Solomon, K. C. Jungling, "A New Fabrication Process for Planar Thin-film Multijunction Thermal Converters", IEEE Trans. Instrum. Meas., Vol. 50, April 2001, pp. 330-332.
- [2] T. F. Wunsch, J. R. Kinard, R. P. Manginell, T. E. Lipe, O. P. Solomon, K. C. Jungling, "Recent Advances in ac-dc Transfer Measurements Using Thin-film Thermal Converters", Proc. Measurement Science Conference, Anaheim, CA (2001).
- [3] J. R. Kinard, T. E. Lipe, and T. F. Wunsch, "Improved High-Current Thin-Film Multijunction Thermal Converters," Digest of the Conference on Precision Electromagnetic Measurements, Ottawa, Ontario, Canada, June 16-21, 2002, pp. 364-365.